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The effect of free water in a maize canopy on microwave emission at 1.4 GHz

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Abstract

Free water in a maize canopy has the net effect of decreasing the brightness temperature at 1.4 GHz (wavelength of 21 cm). It appears that only one form of free water, dew, causes this decrease in brightness temperature. It is not clear how the other form of free water, intercepted precipitation, effects the brightness temperature. This effect occurs at both polarizations, but vertically polarized brightness is affected more than horizontally polarized brightness. We observed a decrease in the horizontally polarized and vertically polarized brightness temperature of a maize canopy of 2 and 4 K, respectively, when intercepted precipitation and dew were present. Since free water in the canopy has been observed to increase the brightness temperature of wheat and grass at 1.4 GHz, we hypothesize that the effect of free water on terrestrial microwave emission depends on the physical dimensions of vegetation canopy components (such as stems, leaves, and fruit) relative to the wavelength of observation. Free water on vegetation will increase terrestrial microwave emission when vegetation canopy components are electrically small, and decrease terrestrial microwave emission when the sizes of some vegetation canopy components are comparable to the observing wavelength and hence scattering in the canopy is significant, as in the case of maize. The electrical size of vegetation components therefore determines the relative enhancement of emission and scattering by free water in the canopy. The most widely used model of microwave emission does not account for the effect of free water on vegetation. Bias introduced by the presence of free water could be a significant source of error in retrieved soil moisture from future 1.4 GHz satellite radiometers.
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1. Introduction

The microwave emissivity of soil is a strong function of water content. A future satellite radiometer, the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2001), will observe Earth's surface at 1.4 GHz, a microwave frequency within L-band that corresponds to a wavelength of 21 cm. For a modest amount of vegetation cover up to and including a full maize canopy, emission from the soil is a large enough fraction of the total emission at 1.4 GHz that changes in the water content of the first several centimeters of the soil

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are readily apparent (Hornbuckle and England, 2004). This reservoir of water, commonly called soil moisture, can be related to plant-available water stored in soil through the use of land surface process models (Wigneron et al., 1999). This total amount of water potentially available to the atmosphere is strongly linked to the variability of precipitation (Koster et al., 2003). SMOS will provide the first global measurements of soil moisture.

In general, both the soil and vegetation contribute to terrestrial microwave emission. Water in the vegetation canopy attenuates and, depending on the physical structure of the vegetation, may also scatter microwave emission from the soil. The effect of water *residing on* the vegetation, either as intercepted precipitation or dew, is not clear. The electrical properties of this "free water" are sufficiently different from water contained within vegetation tissue (Ulaby and El-Rayes, 1987) that small amounts may have a disproportionately large effect. In the Midwest U.S., one area where knowledge of the soil moisture state has the potential to improve forecasts of precipitation (Koster et al., 2004), precipitation patterns are such that during the summer the largest fraction occurs at night (Wallace and Hobbs, 1977; Takle, 1995). Consequently, when SMOS passes over the Midwest U.S. in the early morning (shortly after 6 a.m. local solar time), vegetation will often be wet from either intercepted precipitation or dew. The relative effects of changes in soil moisture and vegetation water content, as well as the effect of intercepted precipitation and dew, on terrestrial microwave emission are not fully understood.

In this paper, we examine the effect of free water in the form of intercepted precipitation or dew on the microwave emission of maize (*Zea mays L.*) at 1.4 GHz. Free water in the canopy, like soil moisture, is an important environmental variable in its own respect. The presence of free water is required for many fungi and bacterial phytopathogens to infect plants (Gleason, 2001). If there is a free water signal, microwave remote sensing could be used along with weather data, information about a specific pathogen, and plant conditions in a disease warning system. Such warning systems determine the risk of the appearance or intensification of a plant disease and can be used to time the application of disease-controlling chemicals, which can improve their effectiveness, reduce costs, and minimize negative impacts on the environment (Gleason et al., 1997).

The overall effect of free water in a vegetation canopy on microwave emission is not clear. Liquid water on the leaves, stems, and fruit of a canopy will increase their dielectric constant and loss. On one hand, this would tend to increase terrestrial emission. A higher dielectric loss in the canopy would decrease the contribution of soil emission to the total emission, but this decrease would be outweighed by the increase in emission from the vegetation (Ferrazzoli et al., 1992; Wigneron et al., 1993). Conversely, in the case of vegetation over moist soil, the presence of scatterers within the canopy reduces the brightness temperature. This phenomenon is called *scatter darkening* (England, 1975). An increase in free water would increase scattering in such a canopy, which would tend to *decrease* the brightness.

Previous measurements of the effect of free water in the canopy on microwave emission resulted in different conclusions. Wigneron et al. (1996) observed that the microwave emission of a wheat canopy increased at 1.4 and at 5 GHz (wavelength of 6 cm) after the wheat canopy had been spray irrigated with water. Both Jones and Vonder Harr (1997) and Lin and Minnis (2000) found that dew *decreased* terrestrial microwave emission over south Texas and central Oklahoma at higher microwave frequencies from 19 to 85 GHz (wavelengths of a centimeter or less). On the other hand, Jackson and Moy (1999) suggested that the small amount of water deposited by intercepted precipitation and dew would not significantly affect emission at 1.4 GHz. Recently, de Jeu et al. (2005) reported that dew did noticeably increase the microwave emission of grass at 1.4 GHz.

It appears that the effect of free water in the canopy on emission, if any, depends on frequency. At 1.4 GHz, free water has been observed to increase microwave emission, while at higher frequencies, free water decreases microwave emission. A frequency dependence may also be the result of a more fundamental principle, the size the vegetation canopy constituents, such as stems, leaves, and fruit, relative to the wavelength of observation. An object will scatter radiation when its size is on the order of a wavelength. When the wavelength is large compared to an object, the object primarily absorbs incident radiation. At microwave wavelengths, a vegetation canopy is semi-transparent and hence the entire canopy contributes to the emission.

We hypothesize that the effect of free water in the canopy on terrestrial microwave emission depends on the *electrical size* of leaves, stems, and fruit, the size of these vegetation canopy components relative to the wavelength of observation. Intercepted precipitation and dew will increase terrestrial microwave emission when vegetation canopy components are electrically small, and decrease terrestrial microwave emission when there are some vegetation canopy components that are significant fractions of the wavelength.

This hypothesis is consistent with previous observations. At high frequencies, there will be significant scattering in all vegetation due to the small size of the wavelength, and the net effect of free water in the canopy will be to decrease microwave emission. At lower frequencies like 1.4 GHz, the effect of intercepted precipitation and dew will depend on the electrical size of the components of the vegetation canopy. The stems and leaves of wheat and grass have small electrical sizes and hence free water would increase terrestrial microwave emission. On the other hand, Hornbuckle et al. (2003) found that scattering is significant in maize at 1.4 GHz. Maize contains several physiological structures, particularly the stem and fruit (ear), that are a significant fraction of the wavelength of 21 cm at 1.4 GHz. Consequently, we expect free water to *decrease* emission from a maize canopy.

To test this hypothesis, we present time-series observations of terrestrial microwave emission at 1.4 GHz and relevant micrometeorological observations measured in a field of maize during a 3-day experiment. Using the recorded data in conjunction with models of radiative transfer and land surface processes, we infer the effect of intercepted precipitation and dew on the microwave emission. Two consecutive nights are analyzed for which the amount of free water present in the canopy was drastically different. First, we compare observations of terrestrial microwave emission with an emission model. Second, we use a land surface process model to predict the relative amount of free water in the canopy for the two nights and compare observations of microwave emission in this context.

2. Measurements

The experimental site, an 800 m (E–W) by 400 m (N–S) field of maize in southeastern Michigan, U.S.A., was unusually flat and uniform in terms of soil properties and vegetation. A picture of the experiment site is shown in Fig. 1. The soil at the site is a silty clay loam of the Lenawee series (16.1% sand, 55.0% silt, 28.9% clay). The field was planted in 2001 on April 29 and 30 (day of year 119 and 120), cultivated on June 11 and 12 (day of year 162 and 163), and harvested on October 17 and 18 (day of year 290 and 291). Average row spacing was 0.77 m. Plant density was 7.49 m^{-2}. Rows were planted E–W.

Fig. 1. Experiment site on day of year 178. Truck-mounted radiometers appear in the foreground. A micrometeorological station tower can be seen in the background.

We measured leaf area index (LAI) as well as vegetation and water column densities periodically throughout the summer. Each recorded LAI value is the average of ten samples made with a leaf area meter (Li-Cor LAI 2000), taken at random locations separated by 5–10 m within the field. Each sample consists of one above-canopy measurement and the average of three below-canopy measurements of the incident radiation: in the row, and one-third and two-thirds of the way across the row space. Vegetation column density is defined as the mass of fresh vegetation (tissue plus internal water) per area, while water column density is the mass of water contained within vegetation tissue per area. We averaged the wet and dry masses of six randomly chosen plants to determine column density.

Microwave emission from a soil surface is affected by its roughness (microtopography) (e.g. Choudhury et al., 1979). We estimated soil surface height standard deviation and correlation length using laser profiler measurements made in a similar experiment the previous summer and a model to adjust for degradation by precipitation (Zobeck and Onstad, 1987). Soil surface height standard deviation varied from 28 mm in early July, to 25 mm during the middle of August, to 15 mm in early October. We assumed that the correlation length of 85 mm measured the previous summer did not change in 2001.

2.1. Radiometry

We measured horizontally polarized (H-pol) and vertically polarized (V-pol) brightness temperature (T_B) at 1.4 GHz with two radiometers mounted on the hydraulic arm of a boom truck (Fig. 1). The radiometers were custom-made by the University of Michigan Space Physics Research Laboratory. We oriented the radiometers so that the line-of-sight of their antennae was at an incidence angle of $\theta = 35^\circ$ ($\theta = 0^\circ$ defined to be perpendicular to the soil surface) and an azimuthal angle with respect to row direction of $\phi = 60^\circ$ ($\phi = 0^\circ$ defined as parallel to row direction). We positioned the truck within the field at the head of a "lane," a portion of the field that was not planted. The lane, 6 rows wide and approximately 250 m long, began at the eastern edge of the field and continued west. Antennae E- and H-plane half-power beamwidths were approximately 21°. Side lobe levels were below −20 dB. Each radiometer's footprint was approximately 40 m^2.

In order to calibrate a radiometer, the linear relationship between its output and the corresponding brightness temperature of the target must be determined periodically. A computer program directed our radiometers to make measurements of each antenna and internal reference load at 2-min intervals. We used the sky (an unpolarized brightness temperature between 5 and 10 K) as one calibration point. Calibration with an external reference (microwave absorber acting as a blackbody at ambient temperature) produced inconsistent results. In its place we used the internal reference loads (a constant unpolarized brightness temperature of 293 K) for the other calibration point. Using the internal reference loads also allowed us to continually adjust the slope of each radiometer's calibration line according to small changes in reference load brightness, and hence the overall transfer function of the system, that resulted from slow and persistent temperature changes in some components of the radiometer.

Radiometer precision (standard deviation of brightness temperature measurements, often called $NE\Delta T$) is a function of random temperature fluctuations within a radiometer. For our radiometers, precision at H- and V-pol was approximately 0.5 and 0.4 K, respectively. We estimated the accuracy of brightness temperature measurements calibrated using the internal reference loads instead of an absorber to be ±2 K.

2.2. Micrometeorology

We placed a micrometeorological station 150 m west of the truck at the approximate center of the field (Fig. 1). We positioned an infrared (IR) thermometer 1 m above the canopy and pointed it at nadir ($\theta = 0^\circ$). An identical IR thermometer underneath the canopy, 20 cm above the ground and also pointed at nadir, measured the soil surface temperature. Each IR thermometer has an accuracy of $<\pm 0.7$ K and a precision of <0.1 K. Hornbuckle and England (2005) discuss the IR thermometer measurements in detail. We measured soil temperature at 1.5 and 4.5 cm depths with thermocouples and thermistors, respectively. These instruments have accuracies of ±0.3 K or less and precisions of <0.1 K. We also measured precipitation, wind speed at 10 m, air temperature and relative humidity at 7.8 m, and downwelling solar and atmospheric radiation with a tipping-bucket rain gauge, a cup anemometer, an air temperature relative humidity probe, a pyranometer, and a pyrgeometer, respectively. A datalogger computed and recorded 20 min averages of micrometeorological variables sampled once every 10 s.

2.3. Soil moisture

We used automated time-domain reflectometry (TDR) instruments (CS-615, Campbell Scientific, Inc., water content reflectometers) to measure the volumetric water content of the soil. A TDR instrument measures the time it takes an electric pulse to travel the length of a transmission line buried in the soil. This propagation time is a function of soil water content. The plane containing the transmission lines of each TDR sensor was parallel to the soil surface. The sample volume of a TDR instrument has the shape of a slightly flattened cylinder with length equivalent to the length of the transmission lines. We used a total of 12 water content reflectometers, half buried at 1.5 cm and half at 4.5 cm below the soil surface. The vertical resolution of each of our TDR instruments was approximately 3 cm (Baker and Lascano, 1989). Hence the TDR placed at 1.5 and 4.5 cm measured the 0–3 and 3–6 cm layers, respectively. We spread the TDR over a 20 m^2 area near the micrometeorological station tower. We measured soil temperature in a similar fashion.

We made several hundred hand-held impedance probe measurements of soil moisture over the course of the summer to calibrate the continuous measurements of soil moisture made at the micrometeorological tower by the buried TDR instruments. We calibrated the impedance probe itself with gravimetric measurements of soil water content. The 0–6 cm soil water content sampled by the impedance probe matched the sampling depth of the TDR measurements made at 1.5 and 4.5 cm. We averaged readings from the 12 TDR instruments to produce plot-scale 0–3 and 0–6 cm water content measurements. This procedure calibrated the TDR instruments in situ to the plot-scale near-surface soil moisture. Hornbuckle and England (2004) describe the details of the soil moisture calibration procedure, including the method used to correct TDR measurements for the effect of soil temperature variations.

3. Observations and analysis

Near the end of the summer, we observed a small precipitation event of approximately 5 mm that thoroughly wet the maize canopy and slightly increased soil moisture. Measured precipitation and soil water content of the 0–3 cm layer for days of year 228, 229, and 230 are shown in Fig. 2. Day of year 228 corresponds to August 16. At the time of these measurements the height of the corn canopy was 3.0 m, leaf area index was 4.8 $m^2\,m^{-2}$, vegetation column density was 8.0 kg m^{-2}, and water column density was 6.3 kg m^{-2} (1.2 kg in leaves, 3.4 kg in stems, and 1.7 kg in ears). These column densities were the highest observed during the summer.

After the precipitation event on day of year 228, soil moisture essentially did not change over the next 42 h save for a small diurnal change in response to soil temperature gradients (Philip and de Vries, 1957). Any changes in the 1.4 GHz brightness temperature of the maize canopy during this time period would have been caused by changes in soil and vegetation temperatures or perhaps by changes in the amount of free water within the canopy, either due to intercepted precipitation or perhaps from dew. In order to determine if free water in the canopy had an effect on the microwave emission, we compared observations of the 1.4 GHz brightness temperature with the most commonly used model of microwave emission. This model takes into account the effects of changes in soil and vegetation temperature and soil moisture on microwave emission.

3.1. Brightness temperature

A vegetated surface can be modeled as a single isothermal layer of vegetation with diffuse boundaries over a soil half space (e.g. Jackson et al., 1982). Using a radiative transfer approach, there are three main components of the brightness temperature:

$$T_B = T_{Bsoil} + T_{Bcanopy\uparrow} + T_{Bcanopy\downarrow} \tag{1}$$

where

$$T_{Bsoil} = T_{soil}(1 - R_{soil})e^{-\tau/\cos\theta} \tag{2}$$

$$T_{Bcanopy\uparrow} = (1-\omega)(1-e^{-\tau/\cos\theta})T_{canopy} \tag{3}$$

$$T_{Bcanopy\downarrow} = (1-\omega)(1-e^{-\tau/\cos\theta})T_{canopy}\,R_{soil}\,e^{-\tau/\cos\theta} \tag{4}$$

where T_{Bsoil} represents the soil contribution to the total brightness temperature. $T_{Bcanopy\uparrow}$ and $T_{Bcanopy\downarrow}$ represent upwelling and reflected downwelling emission from the vegetation canopy, respectively. T_{soil} is the effective soil temperature; R_{soil}, an effective reflectivity of the soil surface; $e^{-\tau/\cos\theta}$, the transmissivity of the vegetation layer; τ, the optical depth; θ, the incidence

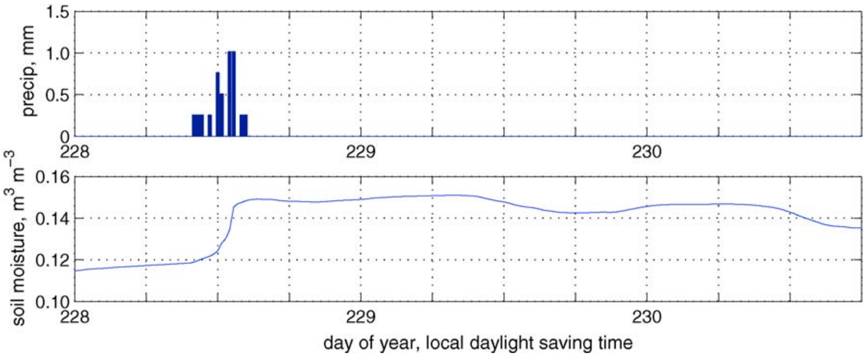

Fig. 2. Precipitation and volumetric water content of the 0–3 cm soil layer on days of year 228, 229, and 230.

angle measured from nadir; ω, the single-scattering albedo; and T_{canopy}, the canopy temperature, defined here as the average of vegetation (top of the canopy) and soil surface (bottom of the canopy) IR temperature. Sky brightness reflected by the land surface is small and can be neglected. R_{soil} is a function of volumetric water content and soil roughness. Both τ and ω are determined primarily by the water content and physical structure (geometry) of the canopy. T_{soil} closely matches soil temperature at 1.5 cm.

Observed and modeled H- and V-pol brightness temperatures at 1.4 GHz are shown in Fig. 3. We used values of τ and ω specifically developed for maize by Hornbuckle et al. (2003) and a model for the effect of soil roughness on R_{soil} developed by Wigneron et al. (2001). A diurnal change in H- and V-pol brightness at 1.4 GHz in response to changes in soil and vegetation temperature is readily apparent. During the gap in brightness temperature measurements on day 229, we measured the brightness temperature at other combinations of incidence angle and angle with respect to row direction, and calibrated the radiometers.

The model correctly predicts a diurnal change in brightness as the soil and canopy warm and cool over the course of a day. On the other hand, there are three periods during which the model deviates significantly from the observations. The first two periods are during the night, on days 228/229 at both H- and V-pol, and at V-pol on 229/230. The third period began after 9:00 on day 230 and persisted until about 17:00, and may be due to the existence of a temperature gradient within the canopy that cannot be accounted for by the model.

After each of the first two periods of discrepancy between the model and observations, the model ‘‘recovers’’ and predictions match observations after about 9:00 or 10:00 in the morning. A vegetation canopy is semi-transparent at microwave frequencies, and hence the entire canopy contributes to emission. It is possible that free water in the canopy, the only variable not taken into account by the model that would change significantly over night and during the morning hours, caused these errors. Perhaps water intercepted by the canopy during the precipitation event on day 228 remained on the canopy overnight and then evaporated after sunrise on day 229. During the night of 229/230 it is possible that dew formed overnight and then evaporated after sunrise. If this is true, then free water in the canopy *decreases* the brightness of maize at 1.4 GHz since observed brightness is *less* than modeled brightness. This is opposite the effect of free water on the emission of wheat and grass at 1.4 GHz (Wigneron et al., 1996; de Jeu et al., 2005).

3.2. Free water in the canopy

We observed free water in the canopy walking through the canopy during data collection around 7:00

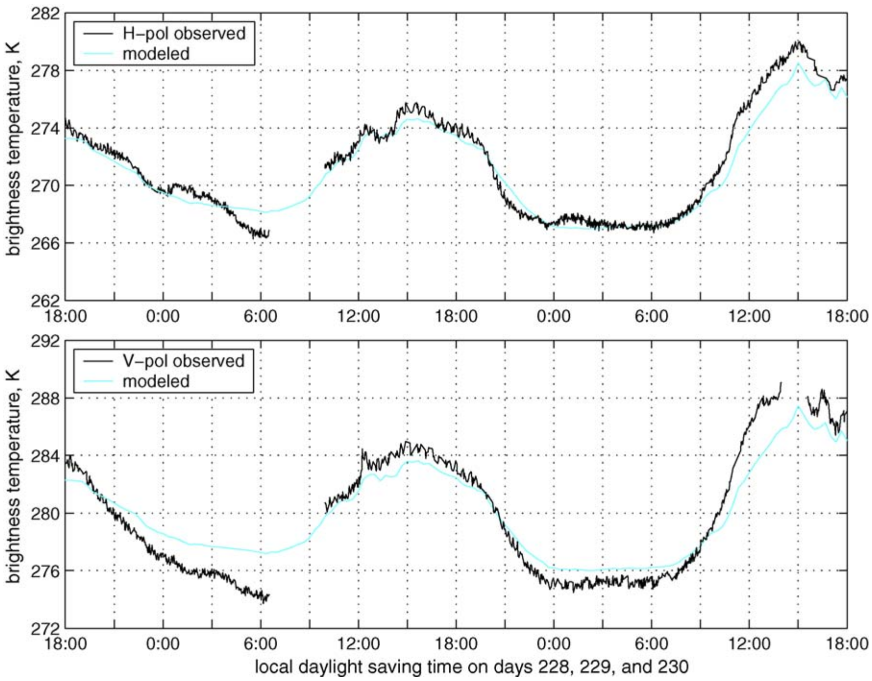

Fig. 3. Observed and modeled H- and V-pol brightness temperatures at 1.4 GHz.

LDT on day 229. It appeared the free water had evaporated by 10:00 that morning. The comparison of model predictions and observed brightness temperatures in Fig. 3 during this period suggest that the net effect of free water in the canopy is to decrease the brightness at 1.4 GHz. No visits to the experiment site were made on days 230 and 231, although the model indicates the possibility of free water during the night of days 229/230. How did the amount of free water in the canopy change over these three days?

3.2.1. The ALEX model

Free water within the canopy can result from either intercepted precipitation or dew. Dew is the result of three processes: dewfall, distillation, and guttation (Monteith, 1957). Dewfall occurs when water vapor originating from above the canopy condenses on vegetation. Distillation is the condensation of water that has evaporated from the soil. Guttation is a process by which water secreted by the plant itself collects on the canopy, but it is not significant in a maize canopy (Atzema et al., 1990). We did not anticipate intercepted precipitation or dew to have an effect on microwave emission, and consequently, we did not make direct measurements of free water. In order to determine the amount of free water in the canopy we estimated intercepted precipitation and dew deposition with the Atmosphere-Land EX-change (ALEX) model (Anderson et al., 2000).

The ALEX model is one of many land surface models that describes the transport of heat, water vapor, carbon, and momentum within the soil–plant–atmosphere system. ALEX is unique because it was developed for practical application in agriculture and weather forecasting (Anderson et al., 2001). It is a simplified version of the comprehensive land surface model Cupid (Norman, 1979; Norman and Campbell, 1983), requiring considerably fewer input parameters (which precluded our use of Cupid) and less computing time. Like Cupid, the use of empirical relationships has been purposely kept to a minimum in ALEX so that the model can be applied to a variety of crops and is not restricted to a certain set of environmental conditions.

The ALEX model estimates dew within the canopy by coupling air temperature and water vapor pressure measured above the canopy to the temperature and water vapor pressure conditions in the canopy airspace, at the leaf surface, and at the soil surface using physical principles of energy balance and turbulent exchange. Free water accumulates on leaf surfaces through the interception of rainfall or irrigation, or by condensation when the vegetation temperature falls below the dew point inside the canopy. Vapor pressure in the canopy airspace is influenced by not only atmospheric vapor pressure, evaporation from leaf surfaces, and canopy transpiration, but also by the evaporation of water from the soil. ALEX uses the Richard's Equation to compute the time-dependent soil moisture profile, taking into account root uptake, drainage, and soil evaporation. In numerical experiments with Cupid, Wilson et al. (1999) found that a wet soil could extend the period of vegetation wetness by 2 h as compared to a dry soil. Because ALEX also considers the role of soil moisture in producing dew, it is distinct from other models that have been used to predict leaf wetness that neglect distillation (Pedro and Gillespie, 1982; Gleason et al., 1994; Chtioui et al., 1999).

The amount of free water in the canopy predicted by the ALEX model is shown in Fig. 4. Observed and modeled V-pol brightness temperatures at 1.4 GHz are also included in Fig. 4 for direct comparison to the estimated amount of free water. According to ALEX, some of the water intercepted by the canopy during the precipitation event on day 228 remained on the canopy throughout the night and into day 229. The increase in canopy free water that began shortly before midnight during the night of 228/229 was caused by the formation of dew. The increase in canopy free water on the following night, the night of 229/230, was also caused by dew since no precipitation occurred on day 229.

Interestingly, the difference between observed and modeled V-pol brightness temperatures roughly corresponds to when ALEX predicted the formation of dew, and not just the existence of intercepted precipitation. ALEX predicted more dew on the first night, the night of 228/229, than on the second night. The difference in the total amount of dew between the first and second night is primarily due to the differences in measured atmospheric radiation, and consequently the differences in net radiation, between the two nights. Dew is likely to occur when net radiation is negative (Garratt and Segal, 1988). Measured atmospheric radiation was considerably greater during the last half of the night of 229/230 (likely due to the appearance of clouds) than on the first night resulting in net radiation that was less negative on the night of 229/230 than on the first night. Additionally, the vegetation canopy temperature was lower on the second night than on the first night. A lower vegetation canopy temperature would also make the net radiation less negative.

Because ALEX considers distillation, the model is sensitive to soil properties and hence the type of soil. We tested the sensitivity of dew formation to soil type by running ALEX with three extreme soils and comparing

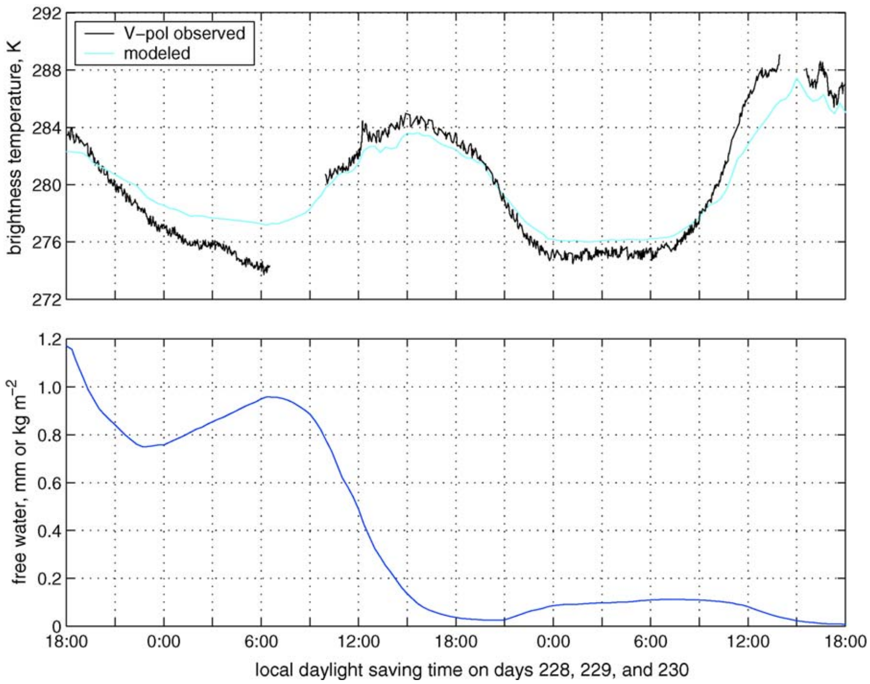

Fig. 4. Observed and modeled V-pol brightness temperatures at 1.4 GHz (top) and free water in the canopy in the form of intercepted precipitation and dew predicted by the ALEX model (bottom) for days 228, 229, and 230.

the results to model estimates made with the specific soil texture at our experiment site. The estimates of dew made with a sandy soil, a silty soil, and a clay soil were essentially the same as the estimate made with our silty clay loam.

3.2.2. Free water in the canopy on 228/229 and 229/230

The amount of free water in the canopy predicted by the ALEX model in Fig. 4 is reasonable but it may not be accurate. Although the ALEX model has been used successfully to predict dew (e.g. Anderson et al., 2001), the theory employed to model the exchanges of heat and moisture among the soil, vegetation, and atmosphere are simplifications of complex processes. There is more confidence in the predictions of the *relative* amount of free water in the canopy during the night of 228/229 compared to the night of 229/230. The uncertainty in the estimation of free water amount is likely to be similar on consecutive nights. Furthermore, errors are more likely to alter only the *amount* of free water on the canopy. Considering the predictions of the ALEX model, the limitations associated with dew estimation, and that no quantitative measurements of dew were made on either night, we can only make qualitative judgments about the amount of intercepted precipitation and dew formation each night and hence conclude the following.

- There was more free water in the canopy on the first night, the night of 228/229, than on the second night, the night of 229/230.
- It appears that both intercepted precipitation and dew contributed to the total amount of free water on the first night.
- If free water was present in the canopy on the second night, essentially all of the free water was in the form of dew.
- There was more dew on the first night than on the second night.

3.3. Effect of free water on emission at 1.4 GHz

The conclusions in Section 3.2.2 concerning the presence of free water in the canopy on the nights of days 228/229 and 229/230 support our earlier conclusion in Section 3.1 that free water decreases the brightness temperature of maize at 1.4 GHz. When a considerable amount of intercepted precipitation and dew were present on the canopy at 6:00 LDT on day 229, observed H- and V-pol brightness temperatures in Fig. 3 were lower than the predicted brightness temperatures. The effect of free water on the brightness temperature is most obvious at V-pol, which suggests that free water decreases V-pol brightness temperature more than H-pol brightness temperature. Observed brightness temperatures are 2 and 4 K less at the end of the night than the modeled brightness temperatures at H- and V-pol, respectively.

However, the steady increase in the difference between observed and modeled brightness temperatures during the night of 228/229 is consistent only with the predicted dew accumulation and not the presence of intercepted precipitation, which would have remained the same or decreased during this period. As a result, it appears that when dew is deposited on the canopy, the brightness temperature decreases, while the effect of intercepted precipitation is not clear. On the night of 229/230, the observed and predicted brightness temperatures in Fig. 3 match much more closely. At V-pol the observed brightness temperature is noticeably less than the predicted brightness temperature, but there is essentially no difference between observed and predicted H-pol brightness temperature. According to Fig. 4, dew occurred earlier on the evening of day 229 than on day 228. After the initial deposition, the amount of dew on 229/230 did not change much the rest of the night. This pattern is reflected in the observed and predicted V-pol brightness temperatures. Instead of a steady decrease during the night as observed the day before, the difference between observed and predicted V-pol brightness temperatures remains constant between 0:00 and 6:00 on day 230. Observed V-pol brightness temperature is approximately 1 K less than the modeled V-pol brightness temperature.

The effect of dew on the brightness temperature at 1.4 GHz is more obvious when the nights of 228/229 and 229/230 are examined together instead of separately. The canopy temperature, the cumulative amount of dew on the canopy since 18:00 LDT as predicted by the ALEX model, and observed H- and V-pol brightness temperatures for each night are shown in Fig. 5. Recall that observed soil moisture was essentially the same each night (Fig. 2). Soil temperatures were slightly warmer (about 1–2 K) the first night compared to the second night, which would result in more emission from the soil and favor a higher brightness temperature on the first night. But at this level of column density, the contribution of emission from the soil to the total emission is small. Given these facts, and if we assume that the vegetation canopy structure and internal water content of the vegetation remained the same, then any differences in brightness temperature between the two nights would have almost entirely been determined by differences in the state of the vegetation canopy: its temperature and the presence of dew.

At the beginning of both nights canopy temperature and brightness temperatures are nearly equal. On the

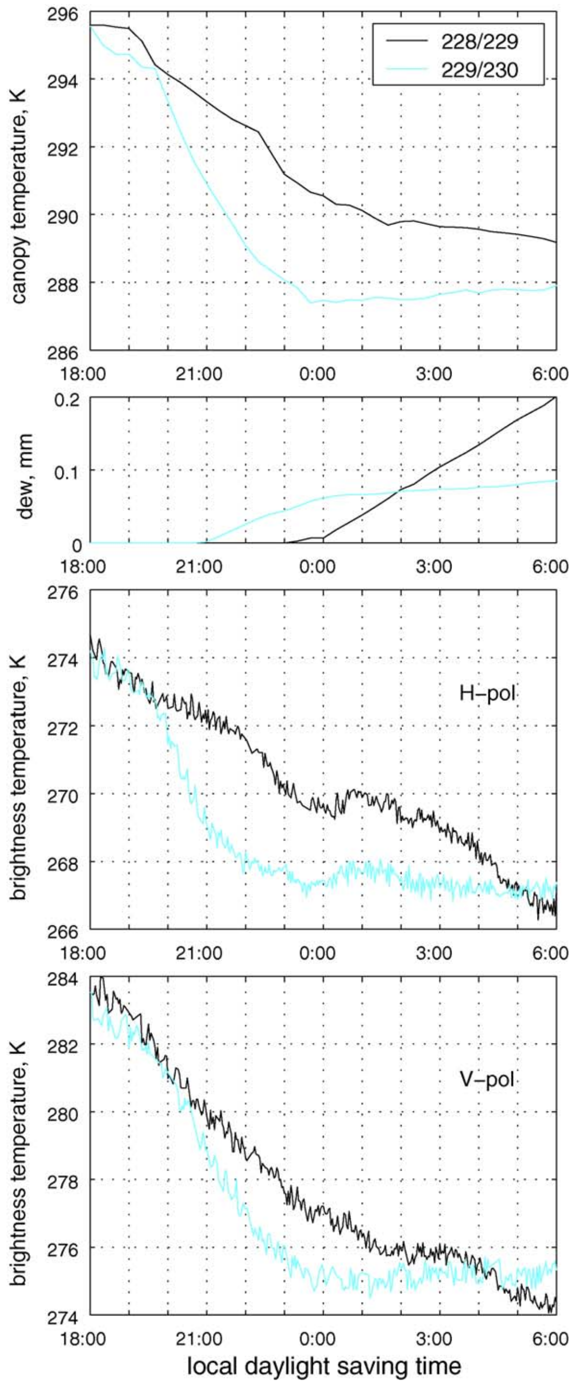

Fig. 5. Canopy temperature, dew in the canopy predicted by the ALEX model, and observed H- and V-pol brightness temperatures at 1.4 GHz during the nights of 228/229 and 229/230. Soil moisture was essentially the same each night. Soil temperature at 1.5 cm was approximately 2 K *higher* on the first night. Since both vegetation temperature and soil temperature would tend to make the brightness temperature *higher* on the first night than the second night, the effect of dew to *decrease* the brightness temperature is evident.

second night, both polarizations of the brightness temperature follow the shape of the temperature of the vegetation canopy as time progresses. This occurs in spite of the prediction of dew by the ALEX model. ALEX may have overestimated the amount of dew on the second night. This is not entirely surprising because of the difficulty in predicting dew. It is also possible that the amount of dew must reach a certain threshold before it significantly affects microwave emission. On the other hand, on the first night both polarizations of the brightness temperature begin to deviate from the shape of the vegetation canopy temperature shortly after 0:00. This deviation is towards lower brightness temperatures, and coincides with the onset of dew as predicted by the ALEX model. By approximately 6:00 LDT on day 229, brightness temperatures at H- and V-pol were approximately 0.5 and 1 K *lower*, respectively, than the brightness temperatures recorded the next night, *despite the fact that the canopy temperature at* 6:00 *on day* 229 *was more than* 1 K higher *than on day* 230. The ALEX model predicts approximately twice as much dew at 6:00 on day 229 than at 6:00 on day 230. Again, soil moisture was virtually constant during this time and soil temperature at 1.5 cm was approximately 2 K *higher* on the first night. Since both vegetation temperature and soil temperature would tend to make the brightness temperature *higher* on the first night than the second night, the effect of dew to *decrease* the brightness temperature is evident.

4. Conclusions

The presence of free water in the canopy decreased the brightness temperature of maize at 1.4 GHz. This effect occurred at both polarizations, although V-pol was affected more than H-pol. Furthermore, it appears that dew, and not intercepted precipitation, causes this decrease in brightness. The effect of intercepted precipitation is not clear. Because intercepted precipitation and dew wet the canopy through different physical processes (Norman and Campbell, 1983), it is plausible that each could affect the brightness temperature in different ways. As more dew condensed on the canopy, the brightness temperature continued to decrease. We observed a 2–4 K decrease in brightness temperature at H- and V-pol, respectively, when approximately 0.9 mm (0.9 kg m^{-2}) of free water (0.7 mm of intercepted precipitation, 0.2 mm of dew) was present in the canopy as predicted by the land surface process model ALEX. A lighter dew the next night decreased the 1.4 GHz brightness temperature at V-pol by 1 K, but did not affect the H-pol brightness temperature.

The effect of free water on the microwave emission of maize at 1.4 GHz was *opposite* the effect observed for wheat and grass (Wigneron et al., 1996; de Jeu et al., 2005). Free water in the canopy *increased* the emission of wheat and grass at 1.4 GHz. The balance between enhancement of volume scattering and the enhancement of emission appears to depend on the vegetation type and frequency of radiation. We hypothesized that the effect of free water on terrestrial microwave emission depends on the electrical size of leaves, stems, and fruit, or, in other words, the size of these vegetation canopy components relative to the wavelength. Free water will increase terrestrial microwave emission when vegetation canopy components are electrically small, and decrease terrestrial microwave emission when some vegetation canopy components are significant fractions of the wavelength. Although we found our hypothesis to be true in this case, it should be tested in future experiments for other types of vegetation at multiple frequencies.

We used the most popular microwave emission model (1) in our analysis. This model is not parameterized to take into account the effect of free water on the 1.4 GHz brightness temperature of maize. At present, this model can only assume that any free water in the form of dew or intercepted precipitation contributes to emission in the same way as water contained within vegetation tissue, resulting in an *increase* in brightness temperature. Our results indicate that free water ‘‘adds’’ differently to different kinds of vegetation depending on the significance of scattering. In order for this model to correctly predict the effect of free water on terrestrial emission at 1.4 GHz, appropriate parameterizations specific to the vegetation type must be developed. These parameterizations must correctly increase both τ and ω, recognizing the distinct dielectric properties of free water and water contained within vegetation tissue, so that the balance of scattering and emission in each type of vegetation can be represented. A polarization dependence must also be assumed. In maize, free water decreased V-pol brightness temperature at 1.4 GHz more than H-pol. This may be due to the orientation of leaves in maize, or perhaps the effect of free water collecting near the stem.

Since SMOS, a future 1.4 GHz satellite radiometer, will pass over local areas on Earth in the early morning hours when intercepted precipitation and/or dew may be present, it is critical that the effect of free water in the canopy on emission be quantified. If the effect of free water is not properly taken into account, estimations of soil moisture could be biased in either direction. For grass canopies with electrically small leaves and stems, free water in the canopy will increase microwave emission at 1.4 GHz and soil moisture will be *underestimated*. For vegetation such as maize, free water will decrease the microwave emission at 1.4 GHz and soil moisture will be *overestimated*. de Jeu et al. (2005) observed a change in 1.4 GHz brightness temperature of up to 10 K at H-pol. Given a nominal soil moisture sensitivity of 2 K per percent change in volumetric soil moisture at 1.4 GHz, it appears possible that bias introduced by the presence of free water could be significant if soil moisture is to be measured to within 4% by volume as planned. Furthermore, SMOS will measure both polarizations at a large variety of incidence angles in order to separate soil and vegetation contributions (Kerr et al., 2001). In this situation free water in the canopy will have an even greater effect on the retrieval of soil moisture through a combination of incorrect estimations of soil brightness and incorrect estimations of vegetation column density.

SMOS will be in a sun-synchronous (polar) orbit. Overpass times of 6 a.m. and 6 p.m. were chosen in part so that measurements would be made near the time of thermal crossover in the morning and evening when soil and vegetation canopy temperature gradients are smallest. For future 1.4 GHz satellites, the selection of overpass times may also need to consider the effect of dew on the brightness temperature, along with other factors such as soil and vegetation temperature gradients (Hornbuckle and England, 2005), soil moisture gradients (Schmugge and Choudhury, 1981), and the state of the ionosphere and its effect on rotation of the polarization vector (Faraday rotation) (Le Vine and Kao, 1997).

Finally, in order to remotely sense dew with microwave radiometry, contributions to the remote sensing signal from the soil and from the vegetation canopy must be separated. Dual-frequency systems may be able to accomplish this by using a low frequency at which dew effects are modest to determine soil moisture, and a higher frequency that is sensitive only to the state of the vegetation canopy. At this point, the feasibility of using such a microwave remote sensing system and its application in disease-warning systems is not known.

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